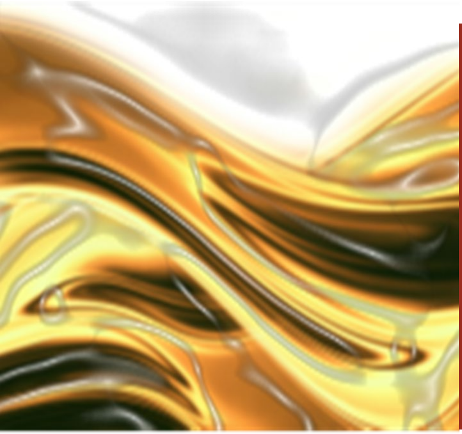
Fluid Power Lab Call



HIGH-PERFORMANCE FLUIDS AND COATINGS FOR OFF-ROAD HYDRAULIC COMPONENTS

Presenter: George Fenske

Argonne National Laboratory

June 13th, 2019

COLLABORATORS:
ANL: Oyelayo Ajayi, Ali Erdemir, Cinta Lorenzo-Martin, Osman Eryilmaz, Robert Erck, Dileep Singh, and Wen Yu
ORNL: Jun Qu, Xin He, Huimin Luo, Harry Meyer III, Teresa Matthews
PNNL: Lelia Cosimbescu, Henok Yemam

Project ID: FT082

OVERVIEW

Focus on Efficient Fluid Power for MOBILE OFF-ROAD Applications

Timeline

- FY17 Congressional Directive
  - LabCall – National Lab Leads
  - FOA Call – University/Industry
- Awards Selected Q3 FY18
  - 1 MultiLab Team
  - 3 University Teams
- NL Project Start – June 2018
- NL Project End Date – June 2020
- Percent Complete – 30% - 75%
  - Depending on lab

Budget

- MultiLab - $1,965K/24 months
  - Argonne - $1,081K
  - Oak Ridge - $491K
  - Pacific NW - $393K

Goals

- The overall goal of the multilab project is to identify low-technology-readiness-level (TRL) fluid/coating technology platforms that improve energy efficiency in a broad range of fluid power systems used in mobile off-road vehicles.

Barriers

- Integrated fluid & material systems that mitigate mechanical and volumetric losses while maintaining component reliability & durability.
- Stable, high-viscosity index (VI) fluids that maintain performance with age.

Partners

- Fluid & Additive OEMs
  - Evonik, Chevron, …..
- USDA

INTRODUCTION & RELEVANCE

Hydraulics are used extensively to power vehicles in mobile off-road applications

Introduction

– The mobile off-road fluid power market comprises construction, agriculture, material handling, oil and gas, and mining sectors. Combined, these markets consume up to 1.8 quads of energy per year in the United States, corresponding to approximately 6.5% of the total energy consumed in the transportation sector in 2017*. ***There is strong motivation within the hydraulic fluid industry to improve efficiency, productivity, performance, uptime/availability, life cycle costs, maintenance costs, and environment & safety compliance.***

Relevance

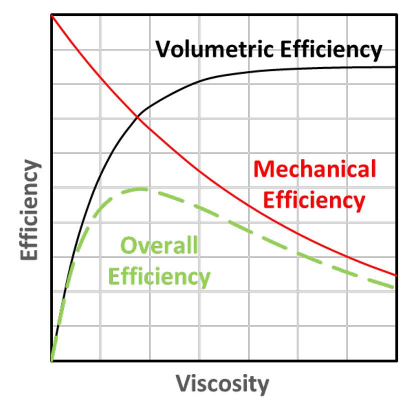
– Multiple solutions are being pursued, including new/novel architectures, hybridization, better engine management, heat & energy recovery, connectivity, and ***better components and fluids***.

– LabCall project on fluid power addresses development of novel, stable fluids and coatings that reduce parasitic losses and improve reliability & durability:
  - Hydraulic fluids with enhanced viscometrics and additives to mitigate pumping & flow losses, and improve durability, reliability, and stability.
  - Wear-resistant coatings that form *in-situ* low-friction boundary films.

* Mobile Fluid Power Workshop and Key Observations — https://www.nrel.gov/transportation/mobile-fluid-power-workshop.html

MECHANICAL AND VOLUMETRIC LOSSES AS FLUIDS FLOW THROUGH HYDRAULIC COMPONENTS SIGNIFICANTLY AFFECT EFFICIENCY

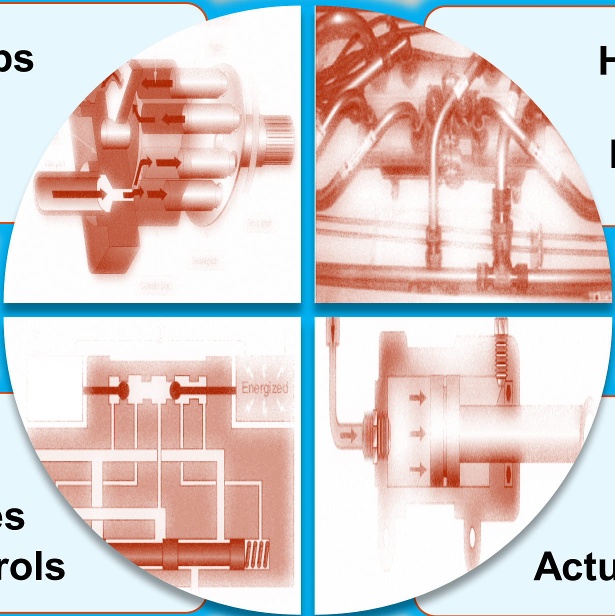
Rheological and tribological properties of fluids and materials significantly impact overall efficiency and reliability/durability of fluid power components.



Power from prime mover

Pumps

Hoses/ Pipes Filters

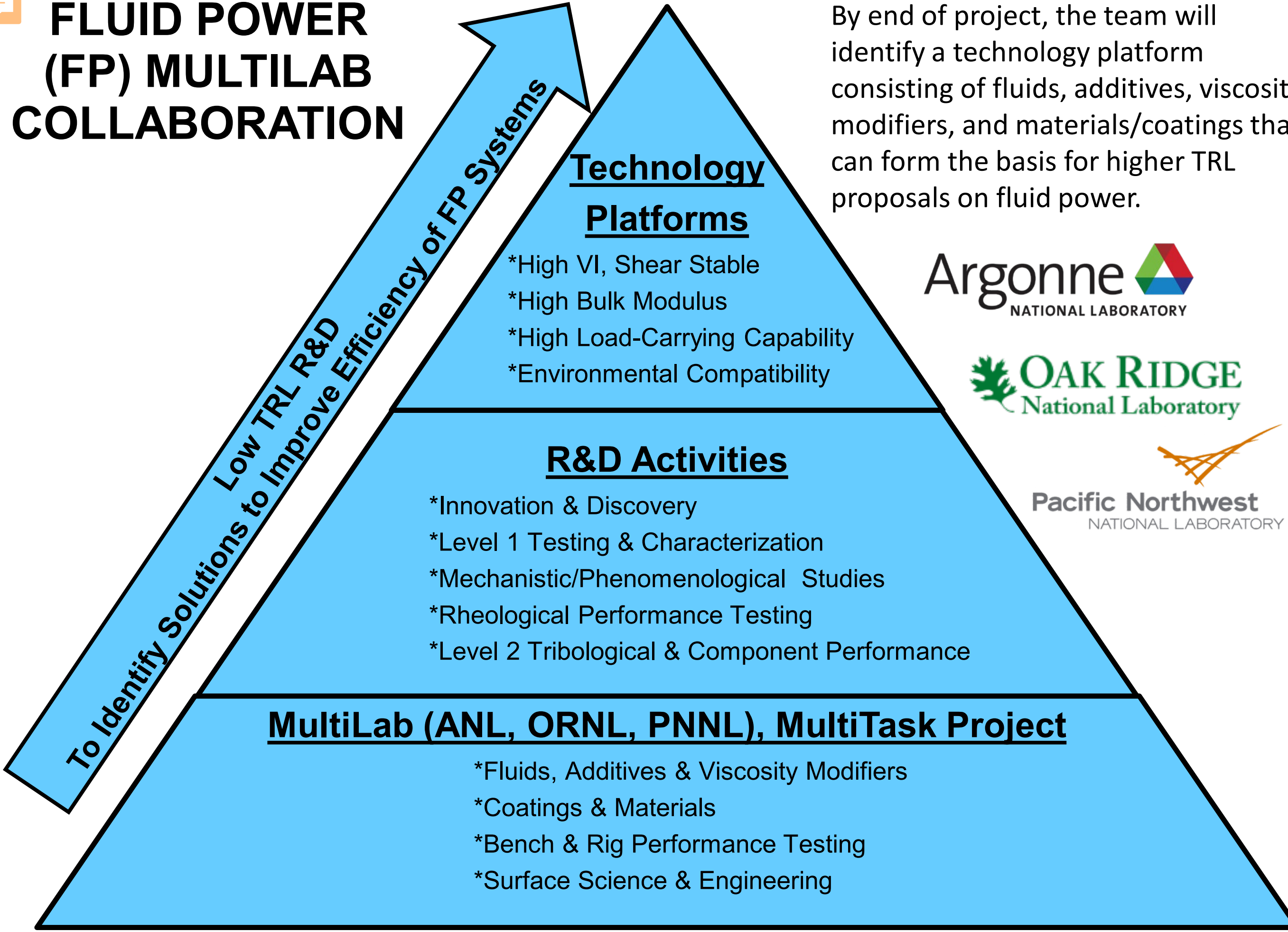


Valves Controls

Actuators

Mechanical power at point of use

FLUID POWER (FP) MULTILAB COLLABORATION



By end of project, the team will identify a technology platform consisting of fluids, additives, viscosity modifiers, and materials/coatings that can form the basis for higher TRL proposals on fluid power.

Argonne NATIONAL LABORATORY

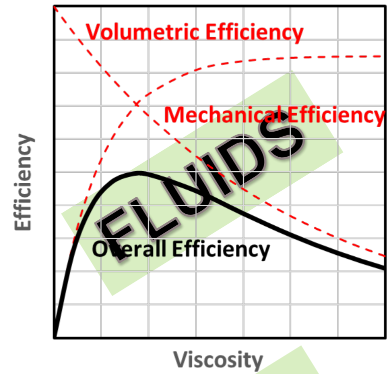
OAK RIDGE National Laboratory

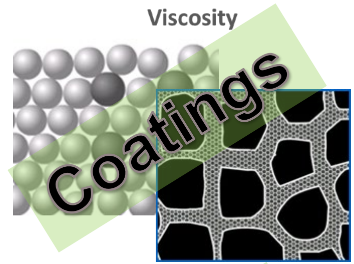
Pacific Northwest NATIONAL LABORATORY

TECHNICAL APPROACH & GOALS

What are the critical attributes/properties being addressed? What do we want to improve?

- **Task 1: Fluid Development Approaches**
  - Stable, high VI fluids that provide wide temperature operating windows
    - **Hybrid/composite basestocks**
    - **Viscosity index modifiers**
  - High bulk modulus fluids to mitigate compressibility losses
    - **Hybrid/composite basestocks**
  - Friction and wear additives that reduce boundary losses and improve durability/reliability
    - **Ionic-fluid based additives**
- **Task 2: Coating Development**
  - High-load-carrying coatings with low boundary friction – improve durability & reliability, enable higher pressure operation
    - **Catalytically doped nitride coatings**
- **Task 3: Bench and Rig Performance Testing**
  - **Low-volume** simulation rig to evaluate efficiency to validate performance of fluids and coatings
  - Lab-scale evaluation of tribological properties
- **Task 4: Fluid & Surface Characterization**
  - Relate bulk and surface properties to fluid and coating performance – better understanding to guide development of fluids & materials





KEY FLUID POWER MILESTONES

Task	Milestone Description	Status	Results
Fluids	Baseline Rheological and Tribological Performance of State-of-Art Hydraulic Fluids	Completed	Results Presented at STLE Conferences & Quarterly Progress Reports
Fluids	Synthesize & Optimize High VI Bioderived Composite Fluids	Complete	
Fluids	Design, Synthesize, & Characterize *Hyperbranched* Polymeric Viscosity Index Improvers	Complete	
Fluids	Design & Synthesize Environmentally Compatible *Ionic Liquid* Platform for Hydraulic Fluids	75% Complete	
Coatings	Design & Synthesize Catalytically Active Nitride Coating Platform	75% Complete	
Rig Testing	Design & Construct a Low-Volume Fluid Power Test Apparatus	75% Complete	

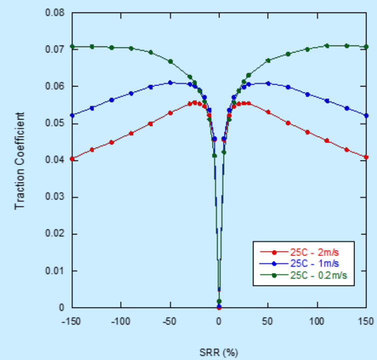
ACCOMPLISHMENT - FLUIDS

Argonne NATIONAL LABORATORY

Characterized rheological performance of reference fluids

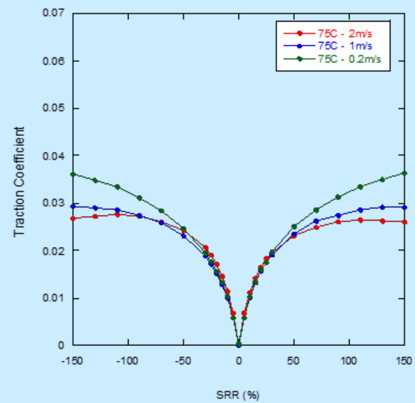
- Completed baselining rheological and tribological performance of ***Reference Fluids*** for comparison against experimental candidate fluids

		Reference Fluids		
Property	**Units**	**HD 32 monograde**	**HDZ 32 multigrade**	**Clarity AW 32 synthetic multigrade**
Viscosity KV 40	cSt	32.32	33.59	32.38
Viscosity KV 100	cSt	5.507	6.556	6.794
Viscosity Index		106	154	175
KRL Shear Loss (%) @ 40 C	%	0.56	6.13	8.34
KRL Shear Loss (%) @ 100C	%	0.36	8.02	10.72
Bulk Modulus (Avg.Tangent) @ 40 C D6793	Gpa	2.08	2.1	1.81
HTHS @ 150 C	cSt	1.91	2.33	2.46
HTHS @ 100 C	cSt	4.49	5.23	5.29
API Gravity		33.1	33.3	35.3
Traction (Max) @ 75 C		0.057	0.06	0.051
Boundary Friction @ 75 C		0.076	0.098	0.077



Traction behavior of multigrade reference fluid HDZ 32

Traction behavior of composite PAO-biofluid



ACCOMPLISHMENT - FLUIDS

Argonne NATIONAL LABORATORY

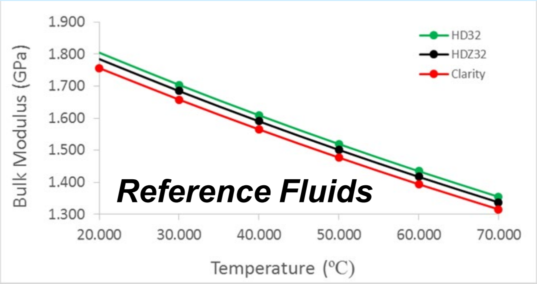
Viscosity and bulk modulus optimization of PAO/biofluid composites

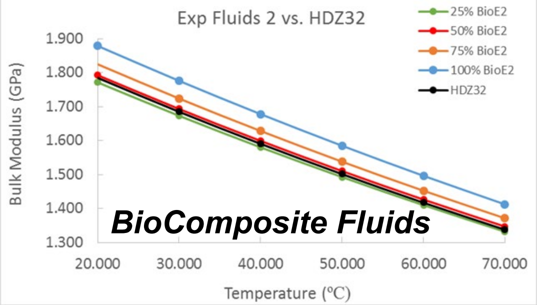
Viscosity and Viscosity Index

Fluid	Viscosity KV 40	Viscosity KV 100	Viscosity Index
HD-32	32.2	5.48	105.2
HDZ-32	33.43	6.51	152.1
Clarity Aw 32	32.5	6.78	173.7
PAO10	69.68	10.53	138.4
25% BioFluid1	39.43	7.45	158
50% BioFluid1	30.4	6.14	155.5
75% BioFluid1	18.76	4.63	175.1
100%BioFluid1	12.69	3.42	153.2
25% BioFluid2	49.58	8.36	143.8
50% BioFluid2	39.14	7.7	170.5
75% BioFluid2	30.31	6.82	194.7
100%BioFluid2	23.81	5.28	163.8

- Achieved comparable viscosity and higher VI to current reference fluids
- Variation of VI with composition – indicative of further optimization

Bulk Modulus



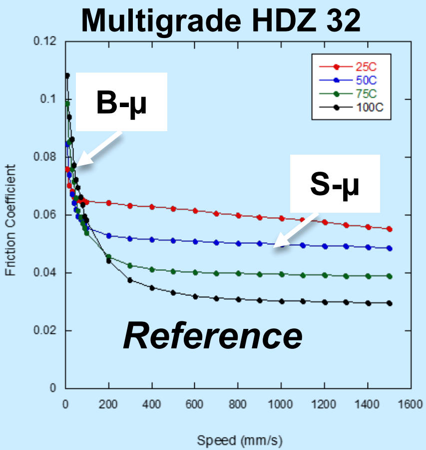


- Minimal effect of BioFluid 1 on modulus
- 3-7% improvement for BioFluid 2 (above 50% composition)

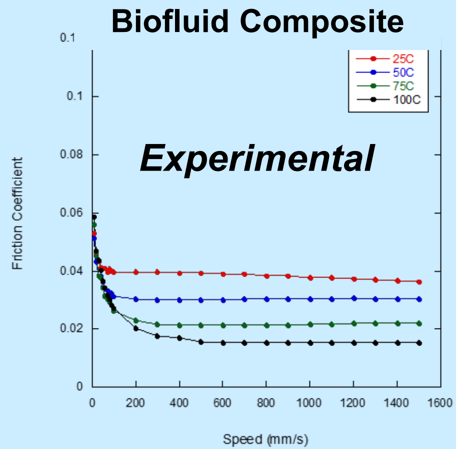
ACCOMPLISHMENT - FLUIDS

Stribeck curves illustrating improved frictional behavior under boundary and electrohydrodynamic conditions

Friction



Under Pure Sliding, Biofluid Composites Outperformed Multigrade Reference Fluid



Fluid	25C		50 C		75 C		100 C	
	B-μ	S-μ	B-μ	S-μ	B-μ	S-μ	B-μ	S-μ
HD 32	0.074	0.057	0.075	0.053	0.076	0.042	0.078	0.033
HDZ 32	**0.076**	**0.055**	**0.085**	**0.049**	**0.098**	**0.039**	**0.108**	**0.030**
Clarity 32	0.061	0.048	0.065	0.041	0.077	0.032	0.089	0.026
PAO	0.052	0.042	0.065	0.035	0.075	0.028	0.090	0.020
25 % Bio 2	0.049	0.038	0.047	0.035	0.048	0.023	0.054	0.018
50 % Bio 2	0.051	0.036	0.050	0.031	0.055	0.022	0.059	0.017
75% Bio 2	**0.050**	**0.037**	**0.058**	**0.029**	**0.063**	**0.019**	**0.063**	**0.014**
100% Bio 2	0.058	0.035	0.060	0.027	0.070	0.018	0.072	0.010

ACCOMPLISHMENT - FLUIDS

Argonne NATIONAL LABORATORY

Identified composite biofluid with superior rheological properties

Summary of Rheological Attributes

	Viscosity 40°C (cSt)	Viscosity 100°C (cSt)	Viscosity Index	Max Traction (75°C)	Boundary Friction (75°C)	Bulk Modulus (GPa) at 70°C
HD-32	32.2	5.48	105.9	0.057	0.076	1.355
HDZ-32	**33.43**	**6.51**	**152.2**	**0.06**	**0.098**	**1.338**
Clarity	32.5	6.78	173.7	0.051	0.077	1.316
PAO	69.68	10.53	138.1	0.041	0.075	1.321
25% BioFluid 1	63.34	8.39	150.7	0.037	0.06	1.315
50% BioFluid 1	30.4	6.14	155.3	0.037	0.068	1.326
75% BioFluid 1	18.76	4.63	175.1	0.036	0.07	1.327
100% BioFluid 1	12.69	3.42	153.2	0.033	0.081	1.336
25% BioFluid 2	49.58	8.36	143.8	0.037	0.048	1.332
50% BioFluid 2	39.14	7.7	170.5	0.036	0.055	1.347
75% BioFluid 2	**30.31**	**6.82**	**194.7**	**0.033**	**0.063**	**1.371**
100% BioFluid 2	23.81	5.28	163.8	0.037	0.07	1.412

- Systematic assessment of rheological performance has identified BioFluid 2 as a promising alternative to obtain high VI performance
- Future efforts will focus on higher TRL studies of BioFluid 2 blends with appropriate additive packages.
  - Shear stability, scuffing, wear, aging, etc.
  - Compatibility with advanced materials & coatings

ACCOMPLISHMENT - FLUIDS

Oak Ridge National Laboratory

Newly-developed ionic liquids demonstrated significantly reduced toxicity and improved anti-wear performance than ZDDP

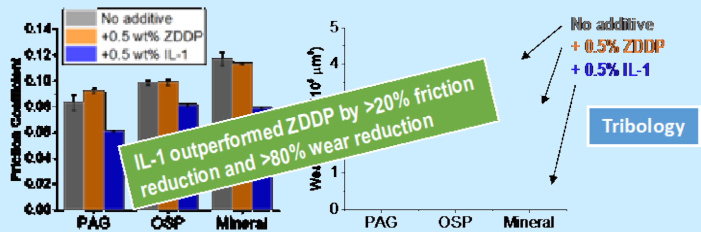
Background and Approach

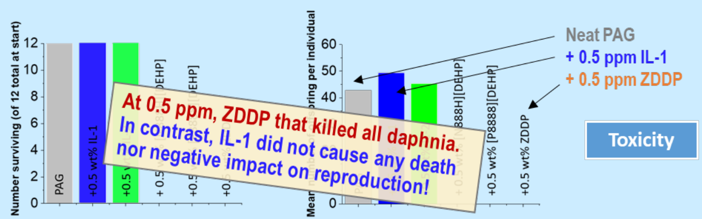
- Eco-friendly hydraulic fluids are highly desirable – EPA – Environmentally Acceptable Lubricant (EALs) specifications & testing
- Conventional AW & EP additives (ZDDP) are not permitted in EALs
- Traditional ashless AWs (TPPT) are acceptable in EALs, but have poor AW properties
- ORNL evaluation of ionic liquids as eco-friendly additives for EAL classification.
  - Good solubility in PAG, OSP, and mineral oils
  - Superior tribological performance, level-1, ball-on-flat testing.
- ORNL chronic toxicity tests of ILs
  - EPA chronic toxicity test using Ceriodaphnia dubia
  - Test lubricants: **PAG, PAG+5%ZDDP, PAG+5%IL**
  - Diluted in water: **10 ppm lubricant (0.5 ppm ZDDP or IL)**

Daphnia magna: asexual reproduction

Low-Toxicity High-Performance Ionic liquids

- Candidate ILs were designed based on the Lubricant Substance Classification list (LuSC-list) for low or no toxicity.
- Selected ILs (e.g., IL-1) are soluble (>5%) in both the polar and non-polar oils.
- Top candidate ILs (e.g., IL-1) demonstrated superior friction reduction and wear protection in all three base oils, in comparison with the conventional ZDDP.
- The toxicity of ILs varied significantly: while some ILs from previous work are similar to ZDDP, the newly designed ILs (IL-1 & IL-2) showed very low toxicity!



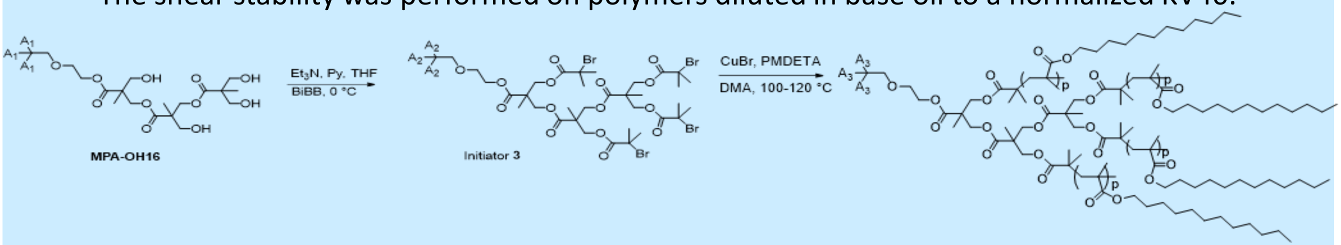


ACCOMPLISHMENT - FLUIDS

PNNL designed, synthesized, and evaluated shear-stable hyperbranched viscosity index improvers (VIIs)

Hyperbranched VIIs

- **Progress:** Relatively high VI polymers with highly branched architectures were designed, synthesized, and evaluated. This combination will provide excellent service over a wide temperature range, including low-temperature cold start-ups. Completed synthesis of 12 highly branched polymers of various structures and varying number of arms (16, 32, and 64).
  - Properties assessed
    - Shear Stability
    - Kinematic Viscosity
    - Viscosity Index
- **Findings**
  - Shear data suggest that ***increased branching increases shear stability*** of the polymer.
  - High viscosity index compounds were prepared which ***require only 0.6% amount of polymer*** to reach VIs of ~160.
  - The baseline material is an OEM polymer, which at equivalent KVs has a VI of 160.
  - The shear stability was performed on polymers diluted in base oil to a normalized KV40.



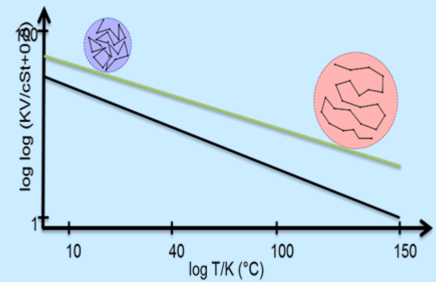
ACCOMPLISHMENT - FLUIDS

Pacific Northwest NATIONAL LABORATORY

PNNL completed hyperbranched viscosity index improvers synthesis and evaluation

Initiator	Monomer	KV40 at 2% (cSt)	KV100 at 2% (cSt)	VI	Viscosity Loss (%)
MPA16-OCL	DMA	35.27	7.00	164	19.2
MPA32-OCL	DMA	33.26	6.67	162	15.4
MPA64-OCL	DMA	76.00	15.55	218	23.5
MPA16-OCL	EHMA	37.11	7.77	186.5	26
MPA32-OCL	EHMA	46.30	10.71	231	26
MPA64-OCL	EHMA	33.68	6.95	173	22
MPA16	EHMA	34.87	7.29	180.7	23
MPA32	EHMA	36.94	7.90	193	20
MPA64	EHMA	33.33	6.87	172	16
MPA16	DMA	34.04	6.88	167.5	18.6
MPA32	DMA	34.11	6.88	167	16.5
MPA64	DMA	32.94	6.69	165.4	14.2

Most Shear Stable



Although highly branched architectures tend to have a low influence on VI, we achieved competitive VIs comparable or higher than commercial FP benchmark. VI is based on polymers collapsing at low temperatures and expending at high temperatures, which results in a viscosity increase. The higher the VI, the larger this effect, but high VI polymers suffer from shear stability losses. We are showing that this can be overcome by using hyperbranched structures.

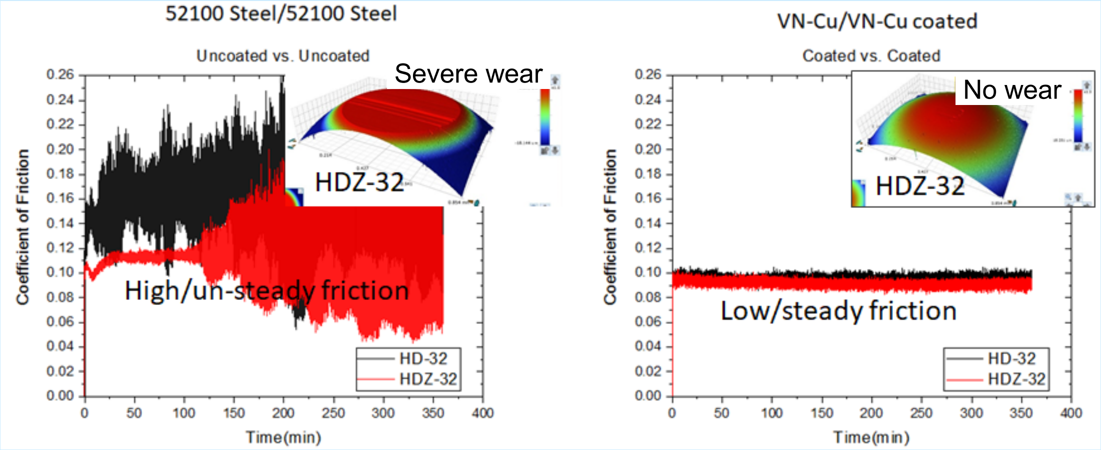
The effect of increased shear stability with branching is especially visible in two series of compounds; the lower the viscosity loss, the more shear stable the material is. Current efforts focus on evaluating commercial benchmark as well as few other analogs whose synthesis was optimized.

ACCOMPLISHMENT - COATINGS

Argonne NATIONAL LABORATORY

ANL completed benchmarking performance of catalytic coating in reference fluids

- Completed baselining the tribological performance of reference materials of construction used in hydraulic fluid power components and experimental surface-modified/coated materials such as copper-doped vanadium nitride.
- Tribological performance quantified using level-1 ball-on-disc test protocols under heavily loaded point-contact conditions (1 GPa contact pressure). Tests were performed with the multigrade HDZ 32 reference fluid.



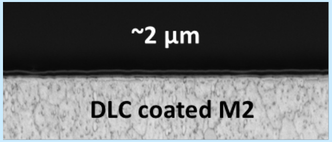
- Catalytically active VN-Cu coating literally eliminated wear and reduced friction despite very severe test conditions (e.g., 1 GPa contact pressure).

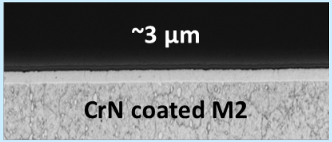
ACCOMPLISHMENT - COATINGS

Oak Ridge National Laboratory

Coating compatibility studies in polar & non-polar fluids

- Completed fluid & additive compatibility studies on uncoated and coated surfaces.
  - Base oil without and with anti-wear additives (including ZDDP and ILs)
  - **Coatings** (provided by Northeast Coating Technologies):
    - **DLC: WC+a-C:H:W+a-CH, by PECVD**
    - **CrN: by PVD**

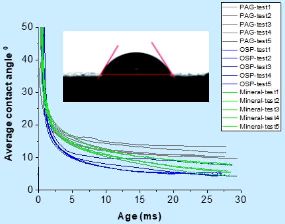


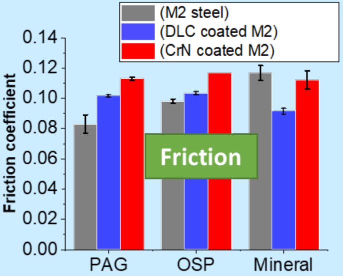


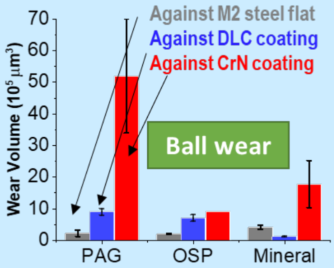
- **Both coatings are substantially harder than the M2 steel substrate.**
  - M2: 900-950 HK, DLC: 2500-2700 HK, CrN: 1800-1900 HK @50 g_f
- **CrN coating appeared to have better wettability than the M2 steel and DLC coating for both polar and non-polar oils.** PAG on the M2 steel surface showed the highest contact angle.
- **Steel ball against steel flat performed the best in PAG, because of higher surface adsorption of the polar PAG molecules.**
- **Steel ball against DLC flat performed the best in mineral oil.**
- **Steel ball against CrN flat performed the best in OSP.**
- **In PAG or OSP, both coatings made the friction and wear higher, suggesting incompatibility with polar oils for DLC and CrN!**

Contact angle

	PAG	OSP	Mineral
Steel	$11.4^{\pm1.4}$	$5.7^{\pm1.6}$	$7.1^{\pm1.5}$
DLC	$6.6^{\pm0.5}$	$6.0^{\pm0.3}$	$6.9^{\pm0.9}$
CrN	$4.8^{\pm0.7}$	$4.1^{\pm0.4}$	$5.0^{\pm0.4}$







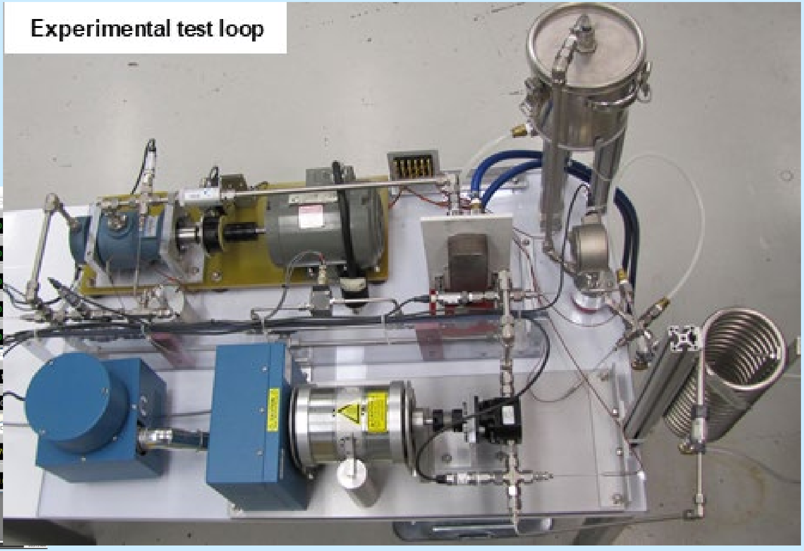
ACCOMPLISHMENT – PERFORMANCE

Fluid Power Test Facility

Completed design and construction of the experimental test facility

- Experimental test loop
  - Lab-scale
  - Modular structure and benchtop setup
  - Multiple measurements
    - ✓ Pressure/differential pressure
    - ✓ Temperature
    - ✓ Torque
    - ✓ Speed
    - ✓ Flow rate

< 2 gallons of test fluids



FLUID POWER - SUMMARY

Goals of the Fluid Power LabCall project are being achieved. Fluids and material/coating platforms have been identified to improve efficiency and reliability of hydraulic fluid systems.

- Identified Technology Platforms/Solutions to improve efficiency & reliability/durability of hydraulic fluid systems & components.
  - Fluids
    - Developed composite biofluids that exceed performance of state-of-art fluids: high VI (195), with reduced traction & friction, and better bulk modulus.
    - Designed, synthesized, and evaluated novel *hyperbranched VIIs* with enhanced shear-stability properties.
    - Designed and evaluated ionic-liquid AW additives with improved tribological and environmental performance.
  - Coatings
    - Designed and evaluated tribological performance of a catalytically doped VN coating that exhibits reduced friction and extremely low wear.
- Goals and objectives of low-TRL project are encouraging and offer a pathway to improve efficiency and durability/reliability of novel hydraulic fluid architectures.

RESPONSE TO REVIEWER COMMENTS

NONE – New project
Not reviewed in FY2108

COLLABORATION

Interdisciplinary and cross-NL team with expertise in synthesis, tribology, materials science, characterization, simulation, and engineering


Layo Ajayi, ANL


Lelia Cosimbescu, PNNL


Robert Erck, ANL


Ali Erdemir, ANL


Osman Eryilmaz, ANL


George Fenske, ANL


David France, ANL


Xin He, ORNL


Cinta Lorenzo-Martin, ANL


Huimin Luo, ORNL


Teresa Matthews, ORNL


Jun Qu, ORNL


Dileep Singh, ANL


Wen Yu, ANL


Henok Yemam, PNNL

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

EVONIK POWER TO CREATE

USDA

OUTREACH PRESENTATIONS & COORDINATION

- **Presentations**
  - *Traction Curves and Rheological Properties of Some Lubricating Fluids*, R. Erck, to be presented at 74^{th} STLE Annual Meeting & Exhibition, Nashville, May 2019
  - *Scuffing performance of brass-cast iron contact pair in hydraulic fluids,* C. Lorenzo-Martin, O. O. Ajayi, S. Lum, G. Fenske, G. B. Bantchev, G. Biresaw, R. E. Harry-O'kuru, to be presented at 74^{th} STLE Annual Meeting & Exhibition, Nashville, May 2019
  - *Tribological performance of composite basefluid for hydraulic systems,* C. Lorenzo-Martin, J. Nguyen, O. O. Ajayi, G. Fenske, to be presented at 74^{th} STLE Annual Meeting & Exhibition, Nashville, May 2019
  - *Scuffing performance of pump materials in hydraulic fluid,* C. Lorenzo-Martin, G. Monroe, O. O. Ajayi, G. Fenske, Submitted to Wear of Material Conference (April 14-18)
  - *Hyperbranched Polymers for Shear Stable Viscosity Index Improvers,* L. Cosimbescu, D. Malhotra, R. Erck, to be presented at 74^{th} STLE Annual Meeting & Exhibition, Nashville, May 2019
  - *Ionic Liquid Additized Environmentally-Friendly Hydraulic Fluids*, X. He, H. Luo, J. Qu, to be presented at 74^{th} STLE Annual Meeting & Exhibition, Nashville, May 2019

- **Coordination**
  - Periodic one-on-one meetings (technical) - Lab-Lab & Lab-Industry
  - DOE Quarterly Progress Meetings
  - CCEFP (Center for Compact and Efficient Fluid Power)
  - NFPA (National Fluid Power Association) – Roadmapping
  - FPIC – Fluid Power Industrial Consortium (MSOE)
  - EERE/AMO/Technologist-in-Residency
  - Evonik – consultation on reference fluids and baseline properties
  - Chevron - common reference fluids

REMAINING CHALLENGES & BARRIERS – FUTURE WORK

R&D to advance low-TRL platforms to mid/high TRL in prototypic environments

- Having identified individual fluid and material platforms that exhibit enhanced rheological, tribological, and environmental performance, a mid/high TRL project is required to evaluate synergism between *advanced fluid platforms* ***and*** *materials/coatings.*
- Technical challenges that remain to be resolved include:
  - Effects of aging on rheological & tribological performance of experimental fluids
  - Assessment of rheological/tribological performance of fully-formulated fluids using experimental fluids
  - Level-2 (fluid-power test facility) performance testing of platform technologies with initial focus on fluids
- Transition is proposed from low-TRL to mid/high-TRL status
  - Current focus on low TRL activities to identify fluids & material platforms
  - Mid/high TRL projects to confirm performance in prototype systems
  - Teaming & collaboration on solicitations.

*Any proposed future work is subject to change based on funding levels

QUESTIONS ??

OVERFLOW BACKUP SLIDES

ANL TASK 3B: SURFACE CHARACTERIZATION

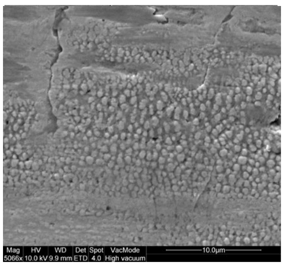
Surface interactions from different fluids- tribofilms

SEM to elucidate wear and failure mechanisms with different fluids

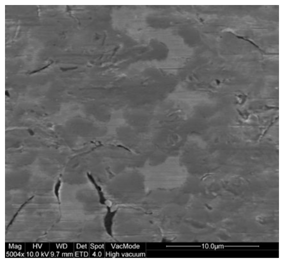
- Formation of tribofilms with commercial fully formulated fluids baselines and PAO
- Minimal tribofilm formation with experimental fluids, but also minimal surface damage

HFRR cast iron flat-on-steel ball

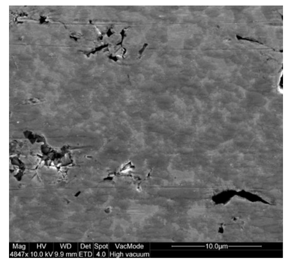
PAO10



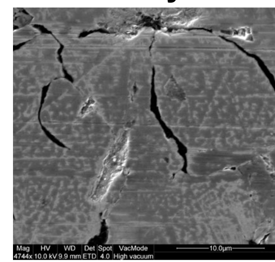
HD32



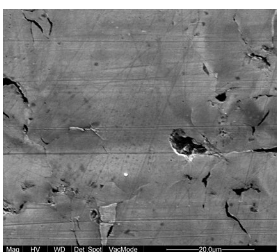
HDZ32



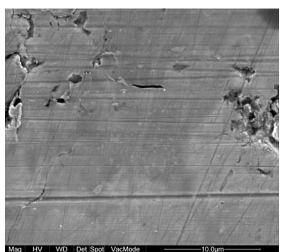
Clarity



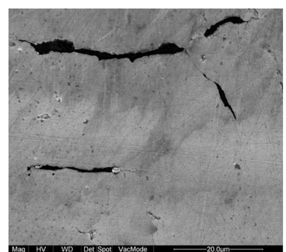
25% BioE



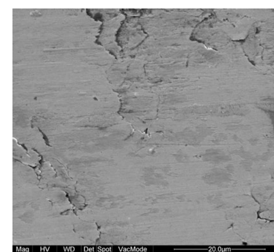
50% BioE



75% BioE



100% BioE

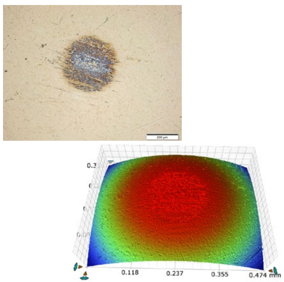


ANL TASK 3B: SURFACE CHARACTERIZATION

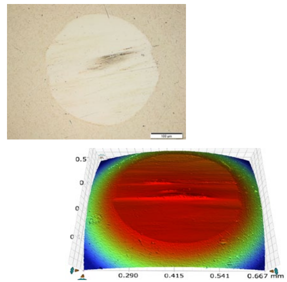
Surface interactions from different fluids

Steel balls

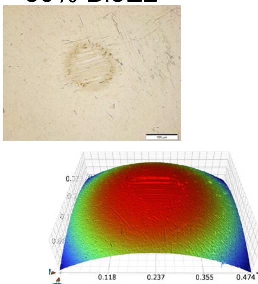
HDZ3



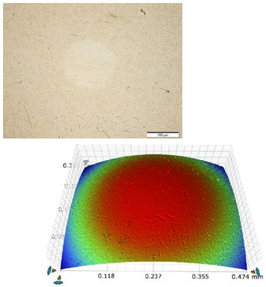
PAO1



50% BioE2



100% BioE2



Formation of tribofilm in both types of balls with commercial fully formulated baseline fluids

In steel ball, minimal formation of tribofilm with bio-based experimental fluids.

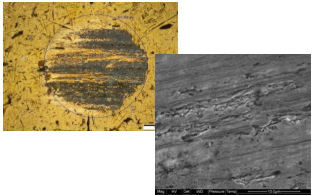
- Surface damage almost eliminated (no additives).

In brass ball, surface tribofilms observed for all fluids, fully formulated baseline and experimental bio-based fluids.

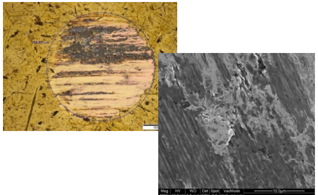
- SEM shows differences in morphology of the films. Chemical analysis to be performed to better understand differences in wear mechanism for each fluid.

Brass balls

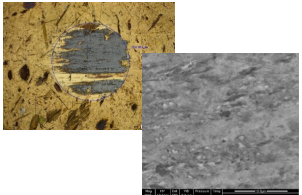
HDZ3



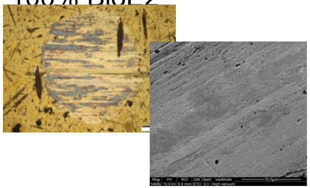
PAO1



50% BioE2



100% BioE2

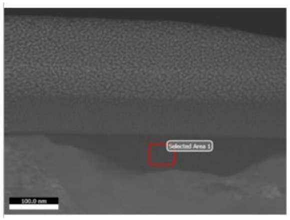


ANL TASK 3B: SURFACE CHARACTERIZATION

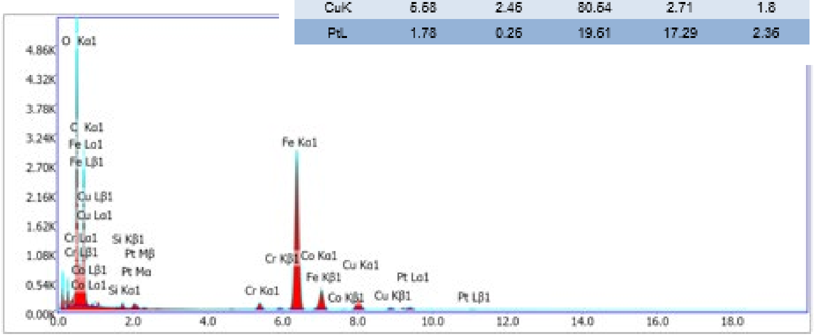
Tribofilm analysis from Bioester experimental fluids

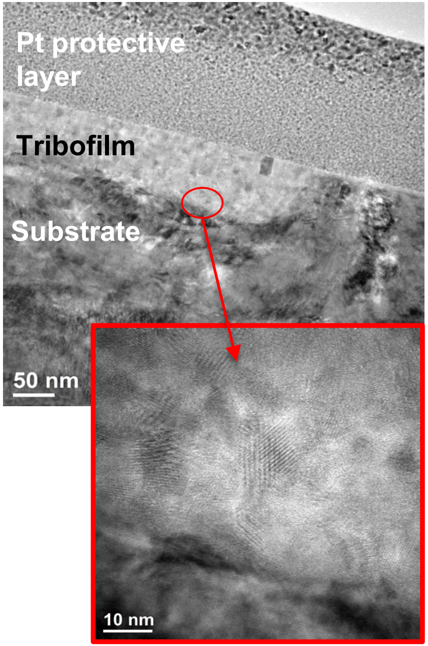
In-depth analysis by FIB/TEM will provide information on structure and chemistry of tribofilms.

- Connection with performance – from previous experience
- Pathway to materials-fluids optimization
- Implications for additives formulation for the fluids



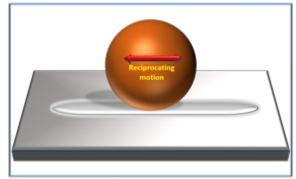
Element	Weight %	Atomic %	Net Int.	Net Error%	KABFactor
C K	2.69	6.04	61.78	2.94	1.3
O K	36.68	64.13	618.76	0.74	1.64
SiK	0.67	0.67	17.37	7.96	1
CrK	1.88	1.01	33.98	6.22	1.44
FeK	60.46	26.27	862.13	0.66	1.64
CoK	0.36	0.17	6.76	33.82	1.63
CuK	6.68	2.46	80.64	2.71	1.8
PtL	1.78	0.26	19.61	17.29	2.36



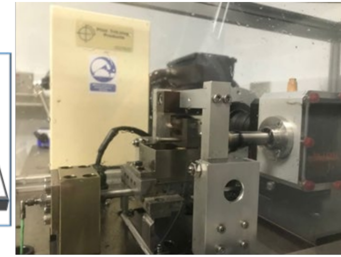


ORNL BOUNDARY LUBRICATION TEST AND ANALYSIS

- **Oil temperature: 180 ^{o}F (82 ^{o}C)**
  - nominal operation temperature of hydraulic fluids
- **Ball: Hardened AISI 52100 steel ball, 10 mm dia., Ra: 15 nm**
- **Flat: Hardened M2 tool steel disc, 1” dia. x 1/8” thick, Ra: 60-70 nm**
  - Common alloys of tribo-components in hydraulic systems, e.g., M2 steel vanes against 52100 steel housing in a vane pump
- **Normal load: 100 N**
  - Hertzian contact pressure: 2.17 (max) and 1.44 (mean) GPa
  - Oscillation frequency: 10 Hz and stroke length: 10 mm
  - λ ratio: ~0.2 → boundary lubrication
- **Sliding distance: 1000 m**



Ball-on-flat system



Plint TE-77 tribometer

Lubricants:

- Base oil + anti-wear additive
- Fully-formulated lubricants
  - Baseline: commercial hydraulic fluid(s)
  - Candidate: IL-additized, more environmentally-friendly fluids

Anti-wear additives:

- Baseline: a primary ZDDP, commonly used in hydraulic fluids
- Candidates: environmentally-friendly ionic liquids
- Concentration: 0.5 wt.%, a typical treat rate in hydraulic fluids